Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture

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LONG-TERM GOALS

UNITES is a unique, interdisciplinary team with expertise spanning the environment (physical oceanography and bottom geology), ocean acoustics (propagation, ambient noise, reverberation and signal processing), and tactical sonar systems. The overall goals of the research are to enhance the understanding of the uncertainty in the ocean environment (including the sea bottom), characterize its impact on sonar system performance, and provide the Navy with guidance for understanding sonar system performance in the littoral ocean. The Harvard work is ongoing within the context of this overall program.

OBJECTIVES

The overall objectives of this research are to:

1. define and characterize the variabilities and uncertainties in the components and linkages of the general physical-geo-acoustical system (the System) relevant to the support of naval operations, and
2. quantitatively transfer the spatial-temporal environmental variabilities and uncertainties through the System, including coupled interactions, in order to determine uncertainty measures, sensitivities and feedback needed to improve operational predictions and parameters

Specific objectives of the Harvard effort are to:

1. develop generic methods for efficiently and simply characterizing, parameterizing, and prioritizing the ocean physical variabilities and uncertainties arising from regional scales and processes
2. construct, calibrate and evaluate uncertainty and variability models for the ocean physics and address forward and backward transfer of uncertainties based on the process of end-to-end data assimilation
3. transfer uncertainties from the acoustic environment to the sonar and its signal processing
4. contribute to overall synthesis and provide guidance for the end-to-end problem

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14. ABSTRACT
UNITES is a unique, interdisciplinary team with expertise spanning the environment (physical oceanography and bottom geology), ocean acoustics (propagation, ambient noise, reverberation and signal processing), and tactical sonar systems. The overall goals of the research are to enhance the understanding of the uncertainty in the ocean environment (including the sea bottom), characterize its impact on sonar system performance, and provide the Navy with guidance for understanding sonar system performance in the littoral ocean. The Harvard work is ongoing within the context of this overall program.

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APPROACH

Our technical approach is based on modeling and simulating physical fields and high order uncertainties for the PRIMER / SHAREM-ACT-ASIAEX regions. Environmental data is assimilated in the Harvard Ocean Prediction System (HOPS) using Error Subspace Statistical Estimation (ESSE) and Optimal Interpolation (OI). 4D Monte-Carlo-based simulations of physical fields, parameters and their respective dominant uncertainties are carried out. The results will be analyzed and the physical estimates transferred to acoustics/signal processing models. Stochastic error models for unresolved processes, forcing and boundary condition errors, and environmental noise, will be further developed and improved. Applied mathematics research for representing, characterizing, capturing and reducing (end-to-end) uncertainty for scientific and Naval purposes will be carried out. End-to-end data assimilation and adaptive sampling will be researched, especially the extension of HOPS schemes to coupled physical-geo-acoustical assimilation/sampling schemes. A.R. Robinson is one of the two co-leaders of the team and he will also coordinate, provide overview and guide the end-to-end system research.

WORK COMPLETED

A.R. Robinson and P.F.J. Lermusiaux attended the ONR Kick-Off Meeting held at University of Washington, Applied Research Laboratory in June 27 and 28, 2001 and an overview of the UNITES Team Approach was given. The presentation, entitled “Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): The UNITES Team Approach” was delivered by Robinson and Phil Abbot (OASIS). The web reference for this talk is given in the header information. A UNITES Team kick-off meeting was held at Harvard University on May 30, 2001 to prepare for this presentation. Additional information regarding this project available via the Internet is listed at the end of this document.

We have been working in close collaboration with Prof. Ching-Sang Chiu and started carrying out the estimation and transfer of uncertainties from the environment to the acoustic fields for the PRIMER region [2, in publication list]. Specifically, the uncertainties in the predicted acoustic wave field associated with the transmission of low-frequency sound from the continental slope, through the shelfbreak front, onto the continental shelf were examined. The coupled methodology for uncertainty estimation was ESSE. Based on the oceanographic data collected during the 1996 Shelfbreak Primer Experiment, the HOPS primitive-equation ocean model was initialized with realizations of physical fields and then integrated to produce realizations of a five-day regional forecast of the sound speed field. In doing so, the initial physical realizations were obtained by perturbing the physical initial conditions in statistical accord with a realistic error subspace. The different forecast realizations of the sound speed field were then fed into the Naval Postgraduate School coupled-mode sound propagation model to produce realizations of the predicted acoustic wave field in a vertical plane across the shelfbreak frontal zone. The combined ocean and acoustic results from this Monte Carlo simulation study provided insights into the relations between the uncertainties in the ocean and acoustic estimates. We also have compared our results with those of Dr. Gawarkiewicz, obtained by direct data analyses. Further discussions are underway.

For the ASIEX region, initial discussions have been carried out with the WHOI group (Gawarkiewicz, Lynch and Duda) so as to learn about, and study the details of, the observations collected at sea. We have also started a first assessment of the main dynamical processes and features present in the East and South China Seas.

We have worked with Prof. Alex Pang and his group to visualize uncertainties computed by HOPS and ESSE [1]. The overall goal is to allow the scientist or operator to visualize large amounts of data and their reliability or uncertainty so as to gain understanding and take appropriate decisions. The specific objective chosen as a start was to incorporate the 3D (i.e. volumetric) error standard deviation estimates in direct volume rendering. Two approaches were investigated. In the first one, an "X-ray" of a given physical field (e.g. temperature) at a given time is taken, with the opacity seen by the "X-ray" being proportional to its uncertainty, i.e. its error standard deviation field. In general, this leads to an image where the most uncertain regions are the most opaque. In the second approach, uncertainty is added on the volume rendered image, in the form of speckles, noise or texture. In this case, for example, the more a region is uncertain, the more it is noisy.

Considering modeling and methodologies, the ESSE approach was extended to physical-acoustical errors and visualization algorithms. Simple stochastic models of internal tides were added to HOPS, complementing our stochastic model for the effect of sub-grid-scale eddies. Software for the analysis of error Probability Density Functions (PDFs) was developed. Software was also written for the transfer of data to the acoustic model/visualization schemes.

RESULTS

The modeled uncertainties in the transmission loss (TL) estimate for the PRIMER locale and their relations to the error statistics in the ocean estimate are discussed in [2] and briefly illustrated here as Fig. 1. The surface sound speed map (Fig 1 - top row, panel 1) indicates the location the front and main water masses. A meander develops in the western side of the domain. A slope-water eddy and a shelf-water eddy are starting to form upstream and downstream of this meander, respectively. The surface error standard deviation (Fig. 1 - top row, panel 2) relates to this mesoscale variability. It is largest along the front, especially downstream of the meander. The relatively large standard deviation at the inflow is due to uncertainties in the position and strength of the front, and also to uncertainties brought upon by the open-boundary conditions.

Higher-order error statistics (Fig. 1 - top row, 3rd and 4th panels) as well as error correlation functions (not shown) can also be computed by ESSE. An interesting result is that, on average, the skewness changes sign at the front. It is estimated to be positive on the shelf and negative on the slope. If errors were Gaussian, the kurtosis (4th/2nd moment, Fig. 1 - top row, 3rd panel) would be 3. On average, it is forecast to be maximum near the skewness extrema. Realizations of the sound speed and transmission loss (TL) along the transmission path, and the corresponding cross-sections in error standard deviation are shown in Fig. 1 - middle four panels. These results are confirmed by the error PDF's (histograms) shown on Fig. 1 - bottom row. Note also that as uncertainties are transferred from the ocean (sound speed) estimate to the acoustic (TL) estimate, the PDF shape is transformed (Fig. 1 - bottom row).

Once ESSE has accurately computed the error PDF's, an important operational and scientific goal is to characterize and model their properties using approximate mathematical formulations. Because the sound pressure field, from which the TL is computed, is composed of multiple acoustic modes, an in-depth understanding of the linkages between the error statistics of TL and sound speed behooves a careful analysis of the errors in the amplitude and phase of each acoustic mode. This modal error analysis is being carried out at present.

The coupled assimilation of physical and acoustical data is also underway. Measurement models are being constructed for linking the physical (acoustical) state variables to the acoustical (physical) data. Once this is completed, the coupled ESSE assimilation will be carried out and studied for the PRIMER domain, first for twin experiments (assimilation of sub-sampled model data), then for the real PRIMER data.

The visualization results are described in detail in [1].

IMPACT/APPLICATIONS

The primary application is to assist the sonar "prediction community" by providing a probabilistic representation of sonar system performance. The present approach provides a systematic method to incorporate uncertainties due to the environment and to transfer the effects of these uncertainties, in the end-to-end problem, through the sonar systems under consideration. The operator can thus use this information to operate the system more effectively and make more informed decisions on search, risk, expenditure of assets (weapons) and assumptions of covertness.

TRANSITIONS

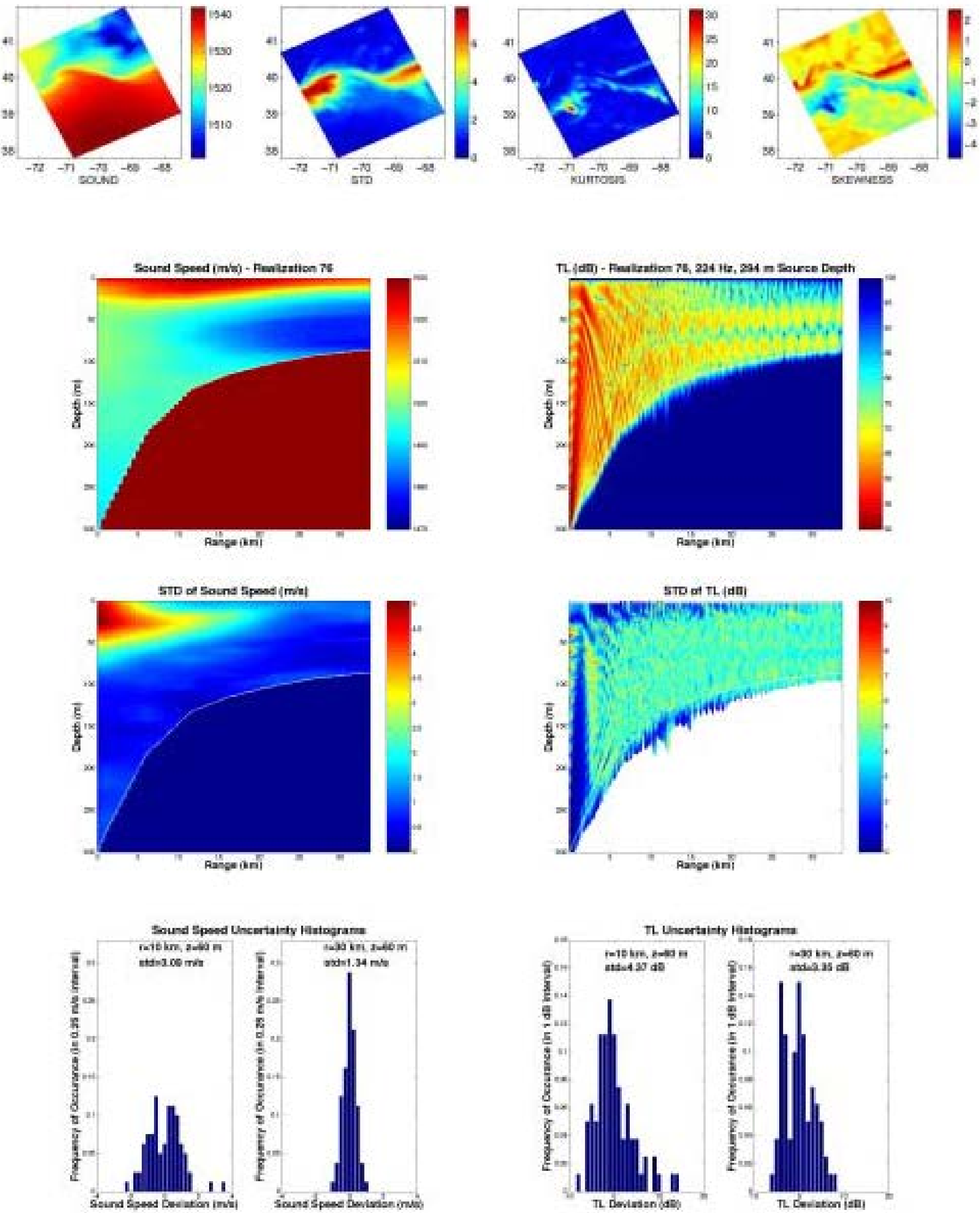
The UNITES team will present rules-of-thumb, lessons learned, technical implications for effective environmental sampling strategies for the fleet and other tactical insights to appropriate fleet personnel and Navy-ONR working groups or programs, e.g. the Advanced Processor Build (APB) program.

Transfer of knowledge will also occur within the UNITES end-to-end team members. Transitions to various scientific and applied groups (e.g. NAVOCEANO, TOMS, etc.) are also expected to intensify.

RELATED PROJECTS

This program is closely related to the Harvard 6.1 research "Dynamics of Oceanic Motions" and the 6.2 research "Development of a Regional Coastal and Open Ocean Forecast System". The Multi-Static Active ASW System is currently being transitioned to the Navy through the Advanced Systems Technology Office (ASTO). The predictive probability of detection curves derived from the UNITES Team are being utilized by ASTO in this program.

Figure 1 (next page). An example Monte Carlo simulation of the transfer of ocean physical forecast uncertainty to acoustic prediction uncertainty in a shelfbreak environment. Based on observed oceanographic data during the 1996 Shelfbreak Primer Experiment, HOPS was initialized with perturbed physical and wind fields that are in statistical accord with a realistic error subspace and then integrated to produce 80 realizations of a regional forecast of the sound speed field. The different forecast realizations of the sound speed were then fed into a sound propagation model to produce realizations of the predicted TL for a low-frequency transmission from the slope, across the shelfbreak, onto the shelf. The ensemble mean, standard deviation, kurtosis and skewness of the sound speed forecast at the surface level are shown (top). A realization of the sound speed along the transmission path, the corresponding TL realization, the standard deviations of the sound speed and TL realizations, and the histograms (PDF estimates) of the sound speed and TL uncertainties at two different locations (shelfbreak and shelf) are shown (bottom), revealing the complexity and inhomogeneity of the uncertainty statistics in this locale.



SOUND
STD
KURTOSIS
SKEWNESS
Sound Speed (m/s) - Realization 76
TL (dB) - Realization 76, 224 Hz, 294 m Source Depth
Depth (m)
Range (km)
STD of Sound Speed (m/s)
STD of TL (dB)
Sound Speed Uncertainty Histograms
std=3.09 m/s
std=1.34 m/s
Sound Speed Deviation (m/s)
TL Uncertainty Histograms
TL Deviation (dB)

PUBLICATIONS

[1] Djurcilov, S., K. Kwansik, P.J.F. Lermusiaux and A. Pang, 2001. Volume Rendering Data with Uncertainty Information, *in* "*Joint Eurographics – IEEE TVG Symposium on Visualizaztion,*" Springer-Verlag, 234-252 & 355-356.

[2] Lermusiaux P.F.J., C.-S. Chiu and A.R.~Robinson, 2001. Modeling Uncertainties in the Prediction of the Acoustic Wavefield in a Shelfbreak Environment. *Proceedings of the 5th International conference on theoretical and computational acoustics*, May 21-25, 2001. Beijing, China. In press.

[3] Lermusiaux P.F.J., C.-S. Chiu and A. R. Robinson, 2001. Coupled physical-acoustical data assimilation and prediction of uncertainties in a shelfbreak environment, in *The use of data assimilation in coupled hydrodynamics, ecological and bio-geo-chemical models of the ocean*. 33rd International Liege colloquium on ocean hydrodynamics, Liege, May 7-11, 2001.

PROJECT INFORMATION AVAILABLE VIA THE INTERNET

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Lermusiaux, 2001. Invited Lecture: Advanced data assimilation schemes: physical and interdisciplinary research. Expert Systems Group Inaugural Meeting and next-generation terrain-following modeling communities workshop, August 20-23, 2001. Boulder, Colorado. See the web site http://marine.rutgers.edu/po/models/roms/Workshops/SIG_2001_agenda.html for more.

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